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Modeling the Response of the Nuisance Alga, 'Cladophora glomerata', to Reductions in Phosphorus Loading

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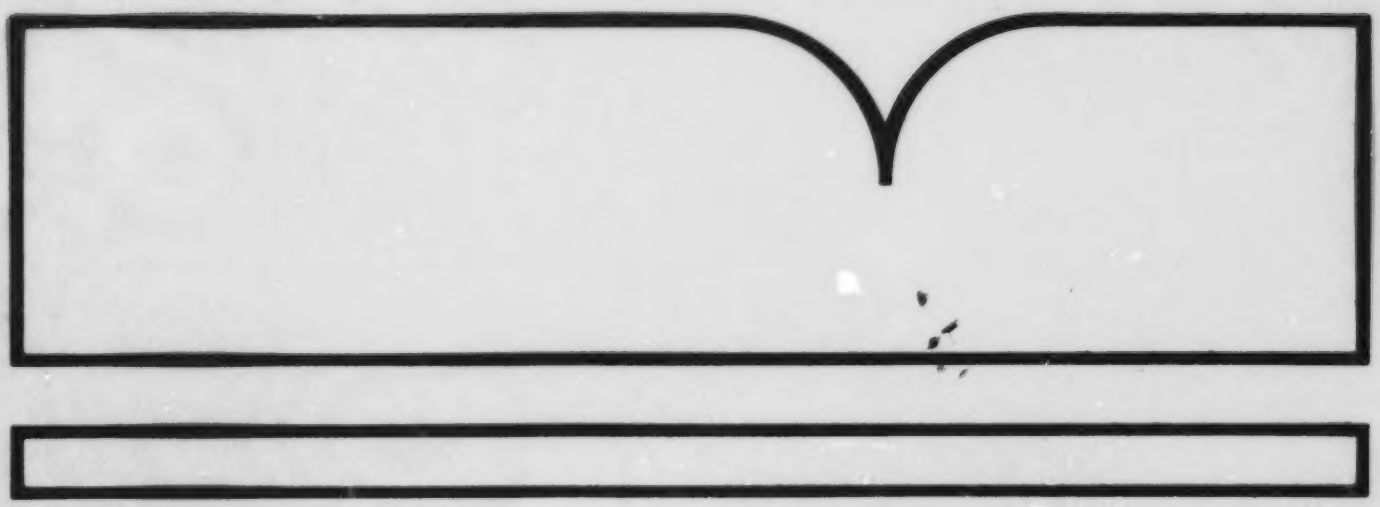

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MODELING THE RESPONSE OF THE NUISANCE ALGA, *CLADOPHORA GLOMERATA*, TO REDUCTIONS IN PHOSPHORUS LOADING

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ABSTRACT

A mathematical model was developed to evaluate the impact of various phosphorus management strategies on nuisance growths of the filamentous alga *Cladophora glomerata*. The model was supported by intensive ecological studies and an extensive field monitoring program. The results of simulating spatial and seasonal variation in algal biomass and associated nutrient parameters agree well with field observations. The calibrated model is used to predict the response of the system under study to a demonstration phosphorus removal program. Implications to large-scale phosphorus management strategies are discussed.

INTRODUCTION

Cladophora glomerata, an attached filamentous green alga (Chlorophyceae), is a recognized nuisance in the littoral region of the Laurentian Great Lakes and many smaller inland lakes. Nuisance growths of this organism in small inland lakes are typified by those observed in the Madison (Wisconsin) lakes, particularly Lake Mendota. In the Great Lakes, water quality is most severely impacted by this alga in Lakes Erie and Ontario (Shear and Konasewich, 1975). In these lower Great Lakes massive accumulations of rotting algal material has resulted in closed beaches, decreased lakeshore property values, and reduced utility of the environment as a recreational resource. The proliferation of *C. glomerata* in Lakes Erie and Ontario is thought to be related to lakewide nutrient enrichment rather than simply point discharges of nutrients. Site specific occurrences of the alga have been reported from Lakes Huron, Michigan, and Superior (Niel and Owen, 1964; Lin, 1977; and Herbst, 1969). The offshore waters of these lakes cannot support significant growth of *Cladophora* because of low phosphorus levels.

The presence of abundant growths of *C. glomerata* may indicate an overall or local reduction in water quality. In small inland lakes septic tank drainage may encourage local growth of plant material or may elevate lakewide nutrient levels so that plant growth is prolific throughout the littoral region. *C. glomerata* is naturally present in rivers, streams, and many inland lakes. Its increase to nuisance proportions, however, reflects a serious perturbation of the quality of our inland waters. As such, amelioration of nuisance conditions by reducing phosphorus loading rates would reflect well upon our commitment toward the lessening of man's impact on the environment.

In 1978, the University of Michigan, in cooperation with the EPA Large Lakes Research Station at Grosse Ile, Mich., began a 3-year program to examine the potential for reducing nuisance growths of *Cladophora* in the Great Lakes. The key function of the project is to develop a mathematical model relating the production of *Cladophora* biomass to phosphorus loadings to the Great Lakes. Such a model would be useful in evaluating the impact of various phosphorus management strategies in controlling *Cladophora* growth. The model integrates available information on the alga as well as indicating areas where new basic studies on the ecology of the organism are warranted. These topics serve as subjects for special investigations designed directly to support the model. A field monitoring program at a site known for nuisance *Cladophora* growth provides data for calibration of the model. Observations following a demonstration phosphorus removal program at the site verify the utility of the model. Projections regarding the impact of various phosphorus management strategies at this and other sites may be examined by using the proper set of loading rates and boundary conditions associated with that location.

FIELD SITE

A field site with a known *Cladophora* problem was selected from which to gather data on the growth of the alga for use in calibrating the mathematical model. A site was chosen which was perturbed by a single major nutrient source, isolated from the complexities of whole-lake growth forcing conditions, e.g., Lake Erie. A

site was selected at Harbor Beach, Mich. on Lake Huron. The water quality of Lake Huron is such that significant growth of *C. glomerata* cannot be supported by offshore waters.

Harbor Beach has a population of approximately 2,000 and is an agricultural and light industrial community. The Harbor Beach wastewater treatment plant is a high-rate trickling filter operation with a design flow of 350,000 gallons/day. The soluble reactive phosphorus loading from the plant for 1979 was 2.163 metric tons (5.93 kg/day). The plant discharges to Spring Creek, a small stream with good upstream water quality. The wastewater treatment plant phosphorus loading results in an annual mean soluble reactive phosphorus concentration of approximately 700 μgP/l at the mouth of Spring Creek. Nuisance growths of *C. glomerata* occur in a symmetrical pattern about the mouth of Spring Creek. the region of perturbation extends 2 kilometers south of the discharge and 0.5 kilometers north where the area suitable for growth is truncated by the presence of a dredged manmade harbor. The presence of extensive cobble shoals (substrate required for attachment) and quiescent bays (reduced mixing with offshore waters) contribute to the potential for algal problems.

The isolation of the site from whole-lake or multiple source nutrient perturbations is confirmed by chemical and biological data. Dissolved phosphorus levels and that stored in algal cells (internal phosphorus) decline with increasing distance from the loading point, eventually reaching background or boundary levels. *Cladophora* biomass decreases as well, with no observable growth at the station most removed from the nutrient source (1.8 km). The relationships between chemical and biological parameters and distance from the nutrient source have been described in detail in an earlier publication (Auer and Canale, 1980).

MODELING FORMAT

The mathematical model used in this project was developed to fully use support available from the specialty studies and monitoring program. The model is composed of a fluid transport and a kinetic submodel. The function of the former is to relate nutrient loading and advective and dispersive transport so that the distribution of dissolved phosphorus in the study area may be predicted. The resultant soluble reactive phosphorus concentrations become the forcing parameter for nutrient uptake rates, a component of the kinetic submodel. Equation 1 summarizes the primary factors regulating the growth of *Cladophora* at the study site on Lake Huron. These factors are the components of the kinetic submodel.

$$\mu = \hat{\mu} (f_1(I) * f_2(T) * f_3(Q) * f_4(X)) - R - S \qquad \text{Eq. 1}$$

where: μ : specific growth rate
$\hat{\mu}$: maximum specific growth rate
$f_1(I)$: function relating growth to light intensity
$f_2(T)$: function relating growth to temperature
$f_3(Q)$: function relating growth to internal phosphorus
$f_4(X)$: function relating growth to carrying capacity
R : respiration rate
S : sloughing loss

TRANSPORT SUBMODEL

Spatial resolution for the model is achieved through establishing completely mixed cells with flows reflecting wind-driven and wave-induced current regimes. The model cells are oriented in two layers parallel to the shoreline. Current regimes are calculated with classical momentum equations which include the effects on non-linearities, wind, bottom friction, and wave action. Several intensive chloride grids as well as weekly and daily chloride measurements at selected stations were also combined with daily wind observations to gain an understanding of nearshore current regimes.

Nutrient loading from the wastewater treatment plant was monitored twice weekly. Soluble reactive phosphorus and total phosphorus concentrations were measured weekly at 25 nearshore stations representing offshore and longshore boundary conditions. Sampling was conducted from ice-out through November, with loading measurements continuing through the winter. The transport submodel then considers loading data and current regimes as well as algal uptake in establishing soluble reactive phosphorus concentrations throughout the study area. These values may be compared with weekly monitoring data from lake stations to calibrate the model.

KINETICS SUBMODEL

The kinetics submodel considers each factor thought to contribute importantly to the growth of *Cladophora glomerata* at the study site on Lake Huron. Three growth terms are considered: Light, temperature, internal phosphorus level, and carrying capacity. The latter is dynamically related to dissolved phosphorus levels through nutrient uptake kinetics. Loss terms include respiration and sloughing. Sloughing refers to the separation of algal filaments from the substrate, leading to shoreline deposition of algal material. The model calculates the specific growth rate and ultimately the algal biomass throughout the study site by relating these factors in the fashion described previously in Equation 1. It is useful to examine the derivation and data base associated with the major components of the kinetic submodel.

LIGHT

An experiment conducted at the BIOTRON facility at the University of Wisconsin examined the relationship between growth rate and light (and temperature). Isolates of *C. glomerata* obtained from Lake Huron and two small inland lakes were cultured over a matrix of light and temperature levels in a crossed-gradients room. Carbon uptake was measured over a range of light intensities (60 to 1,000 $\mu E/m^2$ sec) and the resultant specific growth rate was calculated. These measurements correspond to net photosynthesis. Gross photosynthesis was calculated by adding to the net photosynthesis data a factor representing the respiration rate as derived from the literature (Jackson, 1966). The results of this experiment are presented in Figure 1. These data show growth to be a hyperbolic function of light intensity, with saturation at high light levels. Independent measurements were made to

determine the maximum specific growth rate. The data of Figure 1 were then modified to reflect this information. The range of light intensities used in this experiment are representative of those observed in the field. All field and laboratory measurements recorded photosynthetically-active radiation (PAR) using a quantum meter.

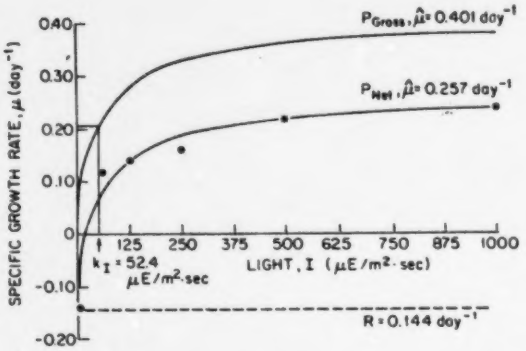

Figure 1. — The relationship between specific growth rate and light intensity for *C. glomerata*.

The light function may be used to calculate daily specific growth rates at depth if input data in the form of light at depth are provided. The level of light at specific depths was calculated on a daily basis. A series of measurements was made to establish a relationship between the extinction coefficient for light and Secchi disk transparency. Depths across the study area were obtained through extensive mapping and daily water level measurements. Daily estimates of incident solar radiation were obtained from the literature and corroborated on site. These estimates were used with the extinction coefficients resulting from daily Secchi disk readings to calculate light at depth. This value served as input to the hyperbolic light function, through which daily values for growth rate as a function of light intensity could be calculated. The results of these calculations indicated that for this site on Lake Huron, light limits the growth of *C. glomerata* below a depth of approximately 1.25 meters.

TEMPERATURE

Temperature has been considered an important factor in regulating growth of this nuisance alga. Data from the BIOTRON experiments were used to describe the function relating growth rate to temperature. Again, carbon uptake rates were measured at 2, 5, 10, 15, 20, 25, 30, and 35°C. A value for gross photosynthesis was calculated by adding the curve for respiration as a function of temperature to the curve for net photosynthesis. The results of this experiment are presented in Figure 2. The growth rate was observed to increase in an approximately linear fashion with temperature to an optimum range of 20 to 30°C. Severe inhibition was noted above 30°C. The importance of temperature in the nearshore Lake Huron environment is seen most clearly in the spring and fall cold periods. Temperature inhibition is not observed as water temperatures seldom exceed 23°C. Water temperatures in the May to August growing season are generally within the optimum temperature range of the alga.

The actual calculations of growth rate as a function of temperature are made possible through the availability of daily temperature data at the study site. Temperature also affects respiration. This relationship is discussed in a later section.

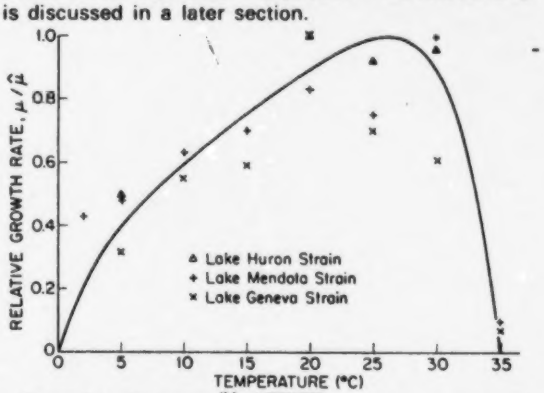

Figure 2. — The relationship between relative growth rate and temperature for *C. glomerata*.

INTERNAL PHOSPHORUS POOLS

Droop (1973) and Senft (1978) have discussed the importance of internal nutrient pools in regulating the growth rates of algae. Experiments examined the relationship between internal phosphorus pools and the growth rate of *C. glomerata*. Algal material was harvested from sites of varying proximity to the nutrient source; these samples thus provided a range of internal phosphorus levels. Internal phosphorus levels (Q) are measured by the persulfate digestion techniques and expressed as the percent P of dry weight (%P). Rates of photosynthesis and respiration were measured under constant conditions of light and temperature, and the resulting specific growth rates were calculated. The results, illustrated in Figure 3, show that growth rate increases with increasing pool size, saturating at high internal phosphorus levels. It is important to note that growth rate increases rapidly as the internal pool size rises above the minimum cell quota (Q_0). Very little additional growth is gained for considerable increases in pool size as the saturation level is approached. This phenomenon will have serious implications for phosphorus management strategies. The position of the algal community along the response curve will determine to a large extent the success of any phosphorus removal efforts.

The mathematical model calculates internal phosphorus pools directly given a growth rate (loss term for internal pools) and the kinetic of nutrient uptake (gain term for internal pools). Experimentally derived relationships for phosphorus uptake kinetics are used in the model. Phosphorus uptake is regulated by two factors: Dissolved (external) phosphorus concentrations and internal phosphorus concentrations. Phosphorus uptake rates have been demonstrated experi-

mentally to increase with increasing external phosphorus levels in the classic Michaelis-Menten fashion. Saturation is reached at very high substrate levels relative to that observed for phytoplankton. Increases in internal phosphorus concentrations reduce phosphorus uptake rates through negative feedback. This process is a form of enzyme inhibition and has been discussed by Rhee (1978). A kinetic structure relating the substrate saturation process and feedback inhibition has been derived experimentally for *C. glomerata* and included in the model. These experiments will be described in detail in a later publication.

The model may be calibrated by comparing output with measured values for internal phosphorus levels obtained from stations throughout the study area. Internal phosphorus levels are measured at 28 stations at weekly intervals throughout the growing season. These data confirm the longshore symmetry of internal phosphorus concentration and define phosphorus as the element limiting growth in the shallow regions of the nearshore. Very little variation in the level of internal phosphorus was noted for distance offshore at a given station. This indicates that light is the important factor controlling growth in the offshore direction.

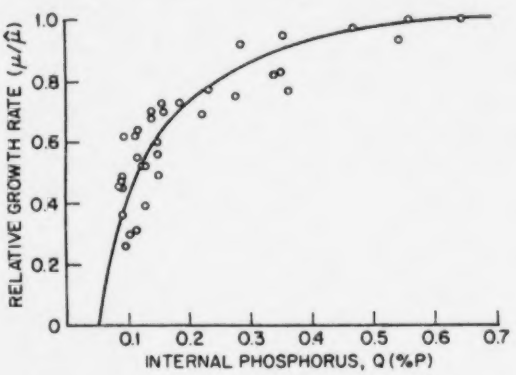

Figure 3. — The relationship between relative specific growth rate and internal phosphorus concentration for *C. glomerata*.

CARRYING CAPACITY

A carrying capacity term has been included in the model to reflect spatial limitations on the substrate as well as self-shading effects. An empirically derived value for the maximum attainable biomass ($X_{\hat{}}$) of 600 gDW/m² is employed. As calculated biomass approaches this level, the model term reduces the growth rate through negative feedback.

RESPIRATION

Respiration represents the most important continuous loss term for the mathematical model of *Cladophora* growth. Experiments currently in progress at the BIOTRON facility will carefully define the relationship between respiration, temperature, and overall metabolic activity. At the present time Jackson's data (1966) are used to derive the relationship between respiration and gross and net photosynthesis. A linear relation between respiration and temperature is used in the model. This function is described in Equation 2. Calculated values for respiration rate are input to the model to obtain the net specific growth rate as a function of temperature.

$$R = R^* (T/20) \qquad \text{Eq. 2}$$

where: R : respiration at T^0C
R^* : respiration at 20^0C
T : measured temperature

SLOUGHING

In that *Cladophora* is not grazed to any extent, the only other loss term is sloughing. Sloughing occurs when severe mechanical disruption causes the algal filaments to become unattached from their substrate and float free in the water column. Shoreline deposition and nuisance accumulation generally result from this process. Although overall physiological condition is thought to bear importantly on sloughing, we have been quite successful in relating sloughing events directly and solely to severe storm (high wind) events. For the current model, sloughing is related empirically to the occurrence of storm events. Experiments in progress with *in situ* algal populations will better relate those storm events, standing crop, and magnitude of sloughing loss.

BIOMASS

The end product of the model is the prediction of standing crop of *Cladophora* biomass. Biomass is accumulated in the model as the product of the growth rate and the current standing crop. The standing crop of *Cladophora* biomass at 14 stations at the Lake Huron study site is measured weekly by harvesting representative samples of the alga and substrate. Density of coverage and areal distribution are measured as well. The results are expressed as grams of oven-dried algal material per square meter of substrate (gDW/m²). The most important calibration of the model involves comparison of model generated biomass data with that observed through the growing season.

RESULTS OF MODEL CALIBRATION

An understanding of the growth dynamics of *Cladophora* entails both spatial and temporal resolution. Generally, temporal or seasonal dynamics are more difficult to simulate. Figures 4 through 6 compare model output of spatial variation for soluble reactive phosphorus, internal phosphorus, and biomass with observed annual average values. In the case of biomass, the midsummer mean value is used to better reflect the maximum standing crop. Model agreement for the two phosphorus components is quite good, accurately reflecting the reduction in dissolved and stored phosphorus with increasing distance from the loading point. Biomass simulation is also quite good, especially considering the heterogeneity of the near-

shore substrate (mixed sand, gravel, and cobbles).

Figures 7 and 8 compare model output with monitoring data describing the seasonal variation in biomass and internal phosphorus for stations near the nutrient source. The mean for each sample date for six stations is plotted. Internal phosphorus levels are relatively constant throughout the year for these stations because of continuous loading from the wastewater treatment plant. The biomass data illustrate temperature limitation in the spring and fall as well as the rise to a maximum standing crop in June through August. Superimposed upon the smooth curve for maximum standing crop is the impact of sloughing loss. The sharp declines in biomass are major sloughing periods and have been empirically associated with storm events. In most cases, biomass levels return rapidly to their pre-slough levels as the restrictions of carrying capacity and substrate/light competition are relaxed following sloughing. This excellent match between model calculated values for biomass and the phosphorus components and observed data allow projections to be made regarding the impact of various levels of phosphorus removal on nuisance growth of *Cladophora* at the site.

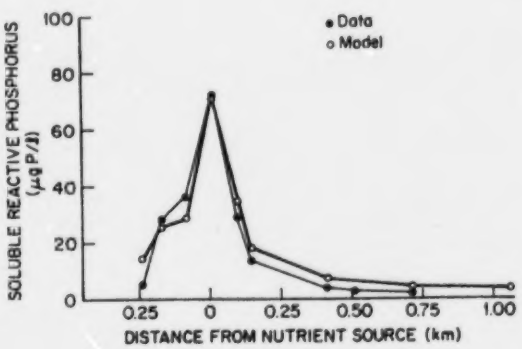

Figure 4. — Comparison of model output and observed data for the distribution of soluble reactive phosphorus about the nutrient source. Values are annual means.

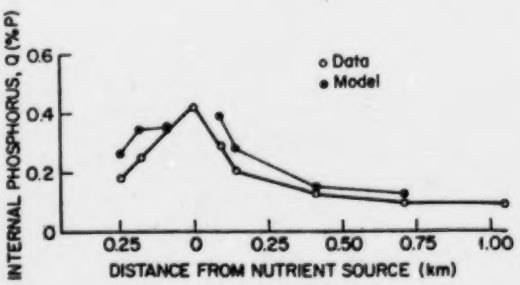

Figure 5. — Comparison of model output and observed data for the distribution of internal phosphorus levels about the nutrient source. Values are annual means.

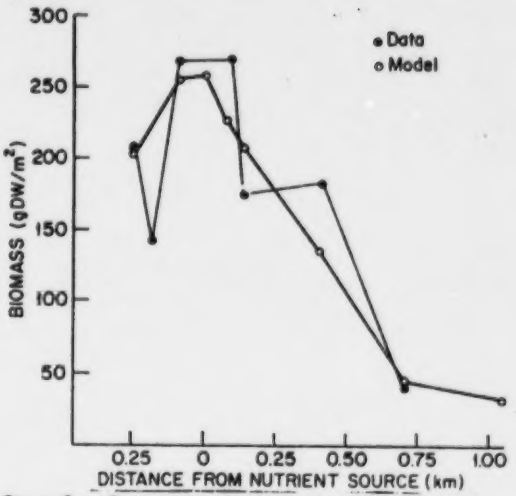

Figure 6. — Comparison of model output and observed data for the distribution of *Cladophora* biomass about the nutrient source. Values are midsummer means.

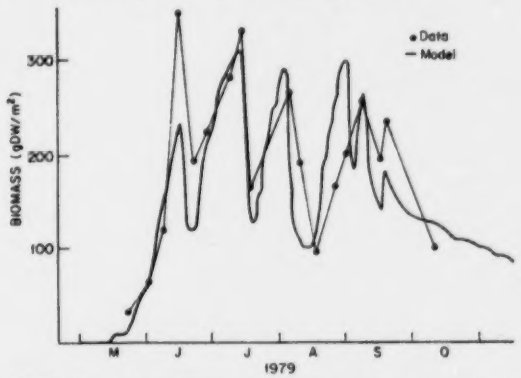

Figure 7. — Comparison of model output and observed values for the seasonal variation in *Cladophora* biomass. Data are mean values for six stations near the nutrient source.

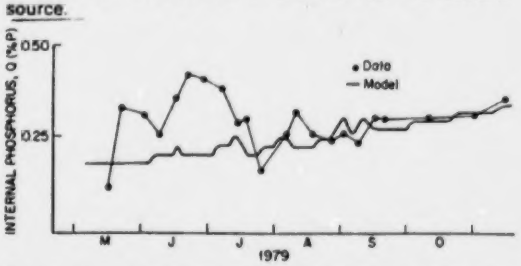

Figure 8. — Comparison of model output and observed values for the seasonal variation in internal phosphorus levels. Data are mean values for six stations near the nutrient source.

DEMONSTRATION PROGRAM AND MODEL PROJECTIONS

In February of 1980 a demonstration phosphorus removal program was instituted at the Harbor Beach wastewater treatment plant. Phosphorus was removed by alum precipitation with a polyelectrolyte coagulant aid. Initial results indicate that an 80 percent reduction in soluble reactive phosphorus at the mouth of Spring Creek may be anticipated. The calibrated model is used

to project the impact of various levels of phosphorus reduction on the standing crop of *Cladophora* at the site. In this manner, the accuracy of the calibrated model may be verified. Figure 9 describes the spatial distribution of midsummer biomass levels associated with several degrees of phosphorus removal. The impact is most noticeable at points remote from the nutrient source. Such a result is consistent with the relationships presented in Figures 3 and 5. Algal material distant from the nutrient source has lower levels of internal phosphorus (0.10 percent) and lies, therefore, in the most sensitive part of the growth response curve. Additionally reductions in biomass in close proximity to the source is much less dramatic. At these locations, internal phosphorus levels are high (approx. 40 percent). Reductions in phosphorus loading will alter the internal phosphorus levels of the algae, but in most cases, pool levels will remain on the saturated (insensitive) part of the growth response curve (see Figure 3).

We have learned from examining this relatively small environmental perturbation at Harbor Beach that such events may drastically affect the capacity of the organism to respond to modest incremental improvements in water quality. From model projections it can be established that significant reductions in biomass may require almost complete removal of phosphorus, particularly near the source. Loading reductions of the magnitude necessary for a return to unperturbed conditions may approach the limit of cost/benefit analysis feasibility.

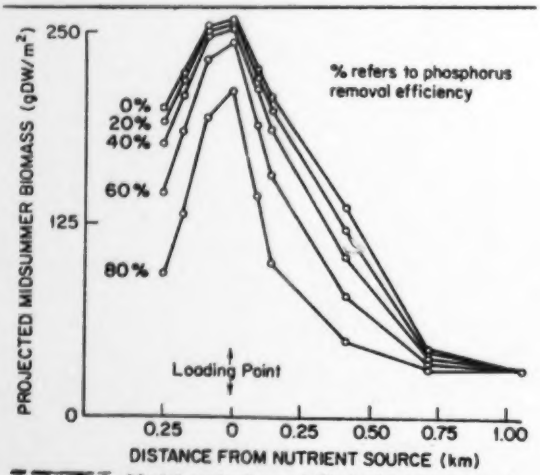

Figure 9. — Model projections of *Cladophora* biomass at various locations at the study site related to several levels of phosphorus removal.

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